

**MODELING AND PARAMETERIZATION OF HORIZONTALLY
INHOMOGENEOUS CLOUD RADIATIVE PROPERTIES**

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OBJECTIVES

One of the fundamental difficulties in modeling cloud fields is the large variability of cloud optical properties (liquid water content, reflectance, emissivity). The stratocumulus and cirrus clouds, under special consideration for FIRE, exhibit spatial variability on scales of 1 km or less. While it is impractical to model individual cloud elements, the research direction is to model a statistical ensembles of cloud elements with mean-cloud properties specified. The major areas of this investigation are: 1) analysis of cloud field properties; 2) intercomparison of cloud radiative model results with satellite observations; 3) radiative parameterization of cloud fields; and 4) development of improved cloud classification algorithms.

RESULTS OF COMPLETED WORK

The following results have been completed under the support of this grant. These results have been published in refereed journals or presented at science conferences.

1) Parameterization of Stratocumulus Cloud Fields. A radiative parameterization scheme of stratocumulus cloud fields is developed based on our Monte Carlo simulations. The parameterization includes Rayleigh scattering and atmospheric absorption above the cloud layer. Zero surface reflection is assumed below the cloud, roughly simulating an ocean or lake surface. The parameterization is valid for cloud cover ranging up to 100%, for zenith angles less than 72.5° and for cloud optical depths between $\tau = 3$ and $\tau = 49$.

2) Structural Characteristics of Marine Stratocumulus Cloud. It is found that stratocumulus cloud size distributions obey a power law, that cell horizontal aspect ratio increases with cell diameter, that these clouds are bi-fractal in nature, and that they appear to be homogeneous over regions of about 100 km x 100 km. These are important constraints in our modeling of these cloud fields.

3) Pattern Recognition Method for Cloud Classification. Texture has been found to be a very powerful descriptor of cloud field structure. A new texture-based pattern recognition method has been developed which is a hybrid of Max-Min statistics and Generalized Co-occurrence Matrices (GCM). Using these techniques, it is found that cloud fields may be classified to within 95% accuracy using high spatial resolution single channel near-infrared data.

4) Effects of Broken Cloudiness Upon Surface Reflectance. Monte Carlo simulations have been performed as a function of cloud cover, cloud optical depth, solar zenith angle and surface albedo. The results show that

broken cumulus cloudiness of about 20% cloud cover may not be detectable over reflecting surfaces with albedo as low as 0.25 - 0.30. Over high albedo surfaces with albedos greater than about 0.40, partial cloudiness may actually decrease the system albedo.

5) Comparison of Radiative Transfer Theory with Observations by Satellite and Aircraft. Observations of cirrus and altocumulus clouds during FIRE by Landsat and the King Air have been compared to theoretical models of cloud radiative properties. Good agreement is found between observations and theory when water droplets dominate. Poor agreement is found when ice particles dominate.

6) Cumulus Cloud Spacing and Clustering. Detailed observations of cumulus cloud size distributions, inhomogeneities, nearest-neighbor relationships and cloud field scales of clustering have been determined for ten cloud fields using Landsat data.

7) Cloud Base Height Determination. Cloud base heights are critical for accurate radiative energy balance studies. A Hough Transform approach is used to estimate cumulus cloud base height from high spatial resolution Landsat data. The approach employs a variety of image processing techniques to match cloud edges with their corresponding shadow edges. Cloud base height then is estimated by computing the separation distance between the corresponding Generalized Hough Transform reference points. Another method for determining cloud base height of cirrus clouds also was developed. The cross correlation between a transparent cloud and its shadow is used to determine their separation distance. It is estimated that cloud base height accuracies of 50-70 m may be possible using HIRIS and ASTER instruments.

8) Automated Detection of Jet Contrails. AVHRR split window imageries are used to examine cirrus and contrail signatures. A two step approach is used for this purpose. A preliminary algorithm subtracts the 11.8 mm image from the 10.8 mm image to enhance contrails. Then a three-stage algorithm searches the difference image for the nearly-straight line segments which characterize contrails.

9) Cloud Classification Using Texture Analysis. We use textural characteristics of cloud and ice covered surfaces as a tool of cloud classification in polar regions. Neural network technique, an artificial intelligence classifier, has been used by us as an approach to cloud classification. We also examine the loss of cloud classification accuracy as a function of spatial resolution by degrading the imagery through progressive averaging. Significant improvement in cloud classification accuracy can be obtained using 1/2 -km spatial resolution data rather than the current 1 km resolution data available today from AVHRR and GOES. Cirrus classification

accuracy is especially compromised as the spatial resolution is degraded. However, the use of texture measures defined at the combination of pixel separations $d = 1, 4$ improves classification accuracies by several percent even for 1 km spatial resolution data. Cirrus accuracy is significantly improved by use of multiple distance features.

10) Developing Monte Carlo Radiative Transfer Code Under IDL. The Monte Carlo radiative transfer code has been rewritten in IDL. The radiances calculated by the Monte Carlo radiative transfer code has been verified against the plane-parallel spherical harmonics and discrete ordinate models. The Monte Carlo radiances are obtained in discrete angular bins. Since not all bins have the same number of photons, the radiances agree better for bins with more photons (higher radiance) and poorer for bins with fewer photons (lower radiance). This behavior is characteristics of Monte Carlo simulations. A number of simulations have been run, most notably to check Kobayashi's results. We have run the case of a plane parallel lower cloud layer with a checkerboard pattern on top. Our flux results are nearly identical to those reported by Kobahashi.

11) Retrieval of Cloud Microphysics. Using a radiative transfer model to interpret AVHRR radiances, we have developed a practical method to retrieve effective droplet radius for liquid water clouds on a global scale. We performed sensitivity tests to investigate the possibility and the accuracy of retrieving effective droplet radius and developed a method to remove the thermal emission contribution to Channel 3 radiances. A methodology has also been developed to assess instrument noise of all AVHRR channels under operational conditions. We have performed a global survey of the effective droplet radii of liquid water clouds.

12) Inferring Cloud LWP and Validation of Cloud Droplet Retrievals. We developed a method using visible, infrared and near infrared bands to retrieve cloud LWP in liquid water clouds using the simple relationship between LWP, cloud optical thickness and effective droplet radius. Cloud optical thickness is obtained from visible band and effective radius is retrieved from visible, near-infrared and infrared radiances. Note that this analysis only retrieves effective radius from the top of clouds, so the results may overestimate or underestimate LWP if r_e is not a good approximation of vertically mean effective radius over the whole cloud layer.

13) Coregistration of AVIRIS and TIMS Imagery and Retrieval of Cloud Properties. A technique was developed for coregistering AVIRIS and TIMS imagery using both line by line adjustments and 2D scene adjustments. It was found that the 3-band ratio method of Gao and Goetz (1991) applied to AVIRIS imagery was superior in detecting cloud pixels on the cloud sunside whereas the thermal IR bands of TIMS were superior in detecting pixels on the

antisunside. It was also shown that the shadows cast by the short-level and relatively fast moving FWC clouds induced an average 1°C temperature difference.

14) Cumulus Three-Dimensional Cellular Structure. LANDSAT TM channel 6 images are used to obtain the statistics. A cell recognition algorithm is developed to automatically examine the cloud cellular structures. This allows both unicellular and multicellular analyses. A linear least squares method is employed to model the shape of cloud cells with quadric surfaces. Clouds smaller than 1 km in diameter generally are unicellular and have smaller fractal dimensions. The larger clouds are mostly multicellular and have larger fractal dimensions. The cloud cells exhibit characteristics similar to those of the small unicellular clouds, with the exceptions: (1) that the cell size distribution appears to be better modeled by an exponential distribution and (2) that the larger cells have smaller horizontal aspect ratios, meaning that they have increasing tendencies to be more circular. For the 3000+ cells examined, it is found that 80% can be best approximated by the shape of a hyperboloid of one sheet. About 15% of the cells are hyperboloids of two sheets with convex domes in the positive z direction. The average number of cells in a cloud is found to increase with increasing cloud size slightly faster than linearly. A cloud with effective diameter of 5 km is composed of approximately 5 cells.

PUBLICATIONS UNDER GRANT NO. NAG-1-542

Refereed Publications:

- Parker, L., R. M. Welch and D. J. Musil, 1986: Analysis of spatial inhomogeneities in cumulus clouds using high spatial resolution Landsat data. *J. Climate Appl. Meteor.*, **25**, 1301-1314.
- Welch, R. M., K. S. Kuo, B. A. Wielicki, S. K. Sengupta and L. Parker, 1988: Marine stratocumulus cloud fields off the coast of southern California observed using Landsat imagery. Part I: Structural characteristics. *J. Appl. Meteor.*, **27**, 341-362.
- Welch, R. M., S. K. Sengupta and D. W. Chen, 1988: Cloud field classification based upon high spatial resolution textural features. Part I: Gray level cooccurrence matrix approach. *J. Geophys. Res.*, **93**, 12663-12681.
- Welch, R. M., S. K. Sengupta and K. S. Kuo, 1988: Marine stratocumulus cloud fields off the coast of southern California observed using Landsat imagery. Part II: Textural analysis. *J. Appl. Meteor.*, **27**, 362-378.
- Welch, R. M., and B. A. Wielicki, 1989: Reflected fluxes for broken clouds over a Lambertian surface. *J. Atmos. Sci.*, **46**, 1384-1395.
- Welch, R. M., M. S. Navar and S. K. Sengupta, 1989: The effect of spatial resolution upon texture-based cloud field classifications. *J. Geophys. Res.*, **94**, No. D12, 14767-14781.
- Chen, D. W., S. K. Sengupta and R. M. Welch, 1989: Cloud field classification based upon high spatial resolution textural features. Part 2: Simplified vector approaches. *J. Geophys. Res.*, **94**, No. D12, 14749-14765.
- Welch, R. M., K. S. Kuo and S. K. Sengupta, 1990: Cloud and surface textural features in polar regions. *IEEE Trans. Geosci. and Remote Sens.*, **28**, 520-528.
- Lee, J., R. Weger, S. K. Sengupta and R. M. Welch, 1990: A neural network approach to cloud classification. *IEEE Trans. Geosci. and Remote Sens.*, **28**, 846-855.

- Sengupta, S. K., R. M. Welch, M. S. Navar, T. A. Berendes and D. W. Chen, 1990: Cumulus cloud field morphology and spatial patterns derived from high spatial resolution Landsat imagery. *J. Appl. Meteor.*, **29**, 1245-1267.
- Berendes, T., S. K. Sengupta, R. M. Welch, B. A. Wielicki and M. Navar, 1992: Cumulus cloud base height estimation from high spatial resolution Landsat data: A Hough transform approach. *IEEE Trans. Geosci. and Remote Sensing*, **30**, No. 3, 430-443.
- Engelstad, M., T. Lee, S. K. Sengupta and R. M. Welch, 1992: Automated detection of jet contrails using the AVHRR split window. *Intnl. J. Remote Sens.*, **13**, 1391-1412.
- Weger, R. C., J. Lee, T. Zhu and R. M. Welch, 1992: Clustering, randomness and regularity in cloud fields: 1. Theoretical considerations. *J. Geophys. Res.*, **97**, No. D18, 20,519-20,536.
- Zhu, T., J. Lee, R. C. Weger and R. M. Welch, 1992: Clustering, randomness and regularity in cloud fields: 2. Cumulus cloud fields. *J. Geophys. Res.*, **97**, D18, 20,537-20,558.
- Kuo, K-S., R. M. Welch, R. C. Weger, M. A. Engelstad and S. K. Sengupta, 1993: The three-dimensional structure of cumulus clouds over the ocean. Part I: Structural analysis. *J. Geophys. Res.*, **98**(D11), 20,685-20,711.
- Weger, R. C., J. Lee and R. M. Welch, 1993: Clustering, randomness, and regularity in cloud fields: 3. The nature and distribution of clusters. *J. Geophys. Res.*, **98**, 18,449-18,463.
- Lee, J., J. Chou, R. C. Weger and R. M. Welch, 1994: Clustering, randomness, and regularity in cloud fields: 4. Stratocumulus cloud fields. *J. Geophys. Res.*, **99**, D7, 14,461-14,480.
- Han, Q. Y., W. B. Rossow and A. A. Lacis, 1994: Near-global survey of effective droplet radii in liquid water clouds using ISCCP data. *J. Climate*, **7**, 465-497.
- Han, Q., W. Rossow, R. Welch, A. White and J. Chou, 1995: Validation of satellite retrievals of cloud microphysics and liquid water path using observations from FIRE. *J. Atmos. Sci.*, **52**, 4183-4195.

Papers Presented:

- Welch, R. M., S. K. Sengupta and D. W. Chen, 1987: Classification of cloud fields based on textural characteristics. *SPIE Conf. on Digital Image Processing and Visual Communications Technologies in Meteorology*, 26-29 October, Cambridge, MA.
- Welch, R. M., K. S. Kuo and S. K. Sengupta, 1989: Textural characteristics of cloud and ice covered surfaces in polar regions. Presented at *IGARSS '89/12th Canadian Symposium on Remote Sensing*, 10-14 July, Vancouver, BC.
- Sengupta, S. K., R. M. Welch and M. S. Navar, 1989: Performance of two texture-based classifiers of cloud fields using spatially averaged Landsat data. Presented at *IGARSS '89/12th Canadian Symposium on Remote Sensing*, 10-14 July, Vancouver, BC.
- Welch, R. M., S. K. Sengupta, R. C. Weger, F. D. Carsey, S. A. Christopher and K. S. Kuo, 1990: Cloud classification in polar regions using AVHRR textural and spectral signatures. Preprints, *7th Conf. Atmos. Rad.*, San Francisco, CA, Amer. Meteor. Soc., 411-415.
- Welch, R. M., S. K. Sengupta, F. D. Carsey, C. A. Sundar, K. S. Kuo and M. S. Navar, 1990: Pattern recognition of clouds and ice in polar regions. Presented at the *SPIE Conf.*, 16-20 Apr 1990, Orlando, FL.
- Sengupta, S. K., T. Berendes, B. Wielicki, R. M. Welch and M. Navar, 1990: Automated cloud base height determination from high resolution Landsat data: A Hough transform approach. Preprints, *7th Conf. Atmos. Rad.*, San Francisco, CA, Amer. Meteor. Soc., 303-308.
- Kuo, K.-S., M. Englestad, S. K. Sengupta and R. M. Welch, 1992: The three-dimensional structure of cumulus clouds over the ocean. Extended Abstract, *Intl. WCRP Symposium on Clouds and Ocean in Climate*, 28 Sep-1 Oct 1992, Nagoya, Japan.
- Weger, R. C., J. Lee and R. M. Welch, 1992: Clustering, randomness and regularity in cloud fields. Extended Abstract, *Intl. WCRP Symposium on Clouds and Ocean in Climate*, 28 Sep-1 Oct 1992, Nagoya, Japan.
- Kuo, K-S., R. M. Welch, R. C. Weger, M. A. Engelstad and S. K. Sengupta, 1993: The three-dimensional structure of cumulus clouds over the ocean. Proc. *IGARSS '93/URSI Symposium*, 18-21 Aug 1993, Tokyo, Japan.

- Christopher, S. A., A. M. Vonder Vorste, S. E. Watters and R. M. Welch, 1994: Cloud radiative forcing in the tropics: The effect of optical property retrievals and scene identification. *Proc. 8th Conf. on Atmos. Radiation*, Nashville, TN, Amer. Meteor. Soc., 451-452.
- Han, Q., W. Rossow, R. Welch, A. White and J. Chou, 1995: Comparison of cloud droplet radii and LWP retrieved by satellite data with observations from FIRE. *Proc. Conf. on Cloud Physics*, Dallas, TX, Amer. Meteor. Soc., 65-69.
- Han, Q., R. Welch and J. Chou, 1995: Retrieval of cirrus microphysics over oceans on a near-global scale using ISCCP data. *Proc. Conf. on Cloud Physics*, Dallas, TX, Amer. Meteor. Soc., 583-585.
- Nair, U. S., M. R. Hjelmfelt and R. A. Pielke, 1995: Numerical simulation of June 9-10, 1972 Black Hills storm using CSU RAMS. *Proc. 7th Conf. Mountain Meteor.*, Breckenridge, CO, Amer. Meteor. Soc., 51-56.
- Han, Q., W. B. Rossow, J. Chou, and R. M. Welch, 1996: A near-global survey of cirrus particle size using ISCCP. Preprints, *8th Conf. on Satellite Meteor.*, Atlanta, GA, Amer. Meteor. Soc., --.

Theses: (Full or Partial Support)

- Berendes, T. A., 1991: Remote sensing of cloud base height. M.S. Thesis, Department of Meteorology, S.D. School of Mines and Technology, Rapid City, SD. 52 pp.
- Chen, D-W., 1988: Texture-based classification. M.S. Thesis, Department of Computer Science, S.D. School of Mines and Technology, Rapid City, SD. 101 pp.
- Christopher, S.A., 1995: Cloud radiative forcing in the tropics. Ph.D. Dissertation, Department of Atmospheric Science, Colorado State University, Fort Collins, CO. 186 pp.
- Kuo, K-S., 1995: The Picard iterative approximation to the solution of the integral equation of radiative transfer. Ph.D. Dissertation, Department of Atmospheric Science, Colorado State University, Fort Collins, CO. 101 pp.
- Nair, U. S., Ph.D. in progress

Navar, M. S., 1989: Image segmentation and region classification of Arctic scenes. M.S. Thesis, Department of Computer Science, S.D. School of Mines and Technology, Rapid City, SD. 71 pp.

Rangaraj, N., 1991: Neural network classification of AVHRR data. M.S. Thesis, Department of Computer Science, S.D. School of Mines and Technology, Rapid City, SD. 67 pp.

Zhu, T., 1992: Clustering, randomness, and regularity in cumulus cloud fields. M.S. Thesis, Department of Meteorology, S.D. School of Mines and Technology, Rapid City, SD. 68 pp.